TECHNICAL REPORT ARCCB-TR-92004

155-MM M284 GUN TUBE FAILURE

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FEBRUARY 1992

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1992

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
155-mm M284 GUN TUBE FAILURE

5. FUNDING NUMBERS
AMCMS: 6126.23.H210.0
PRON: M78F0041M71A

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-92004

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

In June 1989 a failure occurred during a routine straightening operation of a 155-mm M284 gun tube on the straightening press. The Advanced Engineering Branch of Benet Laboratories performed a material evaluation of the gun tube forging (serial no. 0242). The results revealed that the gun tube material met the specified mechanical (with the exception of percent reduction-in-area) and material requirements. Evidence showed that the failure was due to a quench crack. In addition, it was determined that a forging defect acted as a stress concentrator for the quench crack.

14. SUBJECT TERMS
Failure, Forging, 155-mm M284 Failure, Forging Defect, Quench Crack

15. NUMBER OF PAGES
22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std 239-18
298-102

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INTRODUCTION

During a routine straightening operation, a 155-mm M284 gun tube forging (serial no. 0242) fractured while being pressed, as shown in Figures 1 and 2. According to the press operator, failure occurred when the loading conditions reached 260 tons. Typically, a gun tube may be subjected to loads up to 400 tons. At the request of the Chief, Manufacturing Division of the Watervliet Arsenal, the Advanced Engineering Branch of Benet Laboratories conducted a failure analysis on the subject gun tube to determine the cause of failure.

PROCEDURE

Our examination and analysis consisted of the following:

- visual inspection
- hydrogen analysis
- chemical analysis
- magnetic particle inspection
- mechanical property testing
- scanning electron microscope/energy dispersive x-ray analysis
- metallography

BACKGROUND/HISTORY

A review of the processing and inspection data revealed that gun tube forging serial number 0242 was subjected to the standard processing sequence, i.e., rotary forging, heat treatment, magnetic particle inspection, and mechanical property testing.

The results of the magnetic particle inspection conducted by Quality Control personnel reported the following longitudinal indications:

• Two indications approximately 5 inches long located 33 to 38 inches from the muzzle end.

• Three indications approximately 3 to 6 inches long located 60 to 66 inches from the muzzle end.

The tube fractured approximately 62 inches from the muzzle end in the region of the reported indications.

Visual Inspection

Upon receiving the failed gun tube forging, a thorough visual examination was conducted. Two segments of the failed tube were received from the Manufacturing Division: a segment approximately 15 inches long (closer to the breech end labeled M1) and a section approximately 11 inches long labeled M2 depicted in Figures 3 and 4, respectively. The failed region is located roughly 62 inches from the muzzle end.

Examination of the fracture surface, seen in Figures 5 and 6, revealed a dark gray region extending from the bore surface into the tube wall. This region is relatively smooth and is a result of quench cracking during the hardening cycle of the heat treatment. The dark gray appearance is due to subsequent oxidation during tempering. The depth of this dark region is about 3/8 inch. The circumferential crack (fracture surface) veered off into a longitudinal crack (Figure 7) with the same depth of oxidation, indicating it existed prior to heat treatment (tempering). Small cracks running skewed from the longitudinal axis were observed on the bore surface in this general vicinity.

Hydrogen Analysis

A hydrogen analysis was conducted on a sample taken from the fracture surface to determine whether hydrogen embrittlement, which may have caused or contributed to the fracture, had occurred. A reading of 2.3 ppm was received.

This amount of hydrogen suggests the possibility of hydrogen embrittlement as a factor in the failure incident.

Chemical Analysis

The chemical analysis for the material is given in Table I.

TABLE I. CHEMISTRY ANALYSIS

Chemical	Benet	Vendor	Required
Carbon	0.34	0.36	0.32/0.36
Manganese	0.58	0.60	0.55/0.65
Phosphorus	0.009	0.005	0.010_{max}
Sulfur	0.008	0.005	0.008_{max}
Nickel	2.20	2.21	$2.10/2.25_{max}$
Chromium	0.99	1.01	0.9/1.1
Molybdenum	0.51	0.49	0.45/0.55
Silicon	0.19	0.16	0.25_{max}

Examination of this data shows that the material meets the specified chemical requirements for gun steel per drawing number 11579755.

Magnetic Particle Inspection

A circumferential crack on the bore surface was revealed under magnetic particle inspection conducted by Benet Laboratories. The crack, approximately 6.5 inches in length, and illustrated in Figure 8, was located about 6 inches from the fracture surface and 56 inches from the muzzle end. In addition, numerous smaller indications (approximately 1/8 to 1/2 inch) were observed, as shown in Figure 9. These indications appeared to have a helical pattern, suggesting they are associated with the forging flow lines, as shown in Figure 10. A representative indication was sectioned and measured approximately

3/8 inch long and approximately 1/4 inch deep into the cut face. Further examination of this defect was conducted during the metallographic portion of our failure analysis.

Mechanical Property Testing

Tensile and Charpy specimens were machined from disks sectioned near the fracture. The mechanical property results received from Watervliet Arsenal along with Benet's data are compiled in Table II below.

TABLE II. MECHANICAL PROPERTY RESULTS

	(0.1%) YS Ksi	UTS Ksi	%RA	Cv (-40°F) ft-lbs
Benet	169	188	18/20	20
Watervliet	170	185	34/35	16/18
Required*	160-180	-	25_{min}	15_{min}

*per drawing number 11578386
YS: Yield strength; UTS: Ultimate tensile strength; RA: Reduction-in-area; Cv: Charpy impact energy

All mechanical properties conformed to specification with the exception of %RA (Benet's data). This was attributed to a localized concentration of non-metallic inclusions in the form of stringers. This condition did not have an influence on the subject failure during pressing.

Scanning Electron Microscopy

Examination by scanning electron microscopy (SEM) of a fracture initiation site, shown in Figure 11, revealed macroscopic crack indications propagating into the oxidized layer of the fracture surface. These indications were crack-type in nature and of substantial depth, as illustrated in Figures 12a and 12b. The orientation and flow pattern of these indications are identical to those observed during magnetic particle inspection.

SEM was also conducted on the fracture surface of the tensile bars. The fracture surface disclosed nonmetallic inclusions determined to be manganese sulfides (MnS) by energy dispersive x-ray analysis (EDXA). Figure 13 illustrates the morphology and distribution on the fracture surface. The fracture mode was of a ductile mechanism.

<u>Metallography</u>

A cross section of the defect (previously observed under SEM in Figure 11) at the fracture initiation site was mounted, polished, and etched (2% Nital). It was determined to be a crack with an oxide layer on its surface, as shown in Figure 14. This fracture indicates existence prior to tempering. In addition, decarburized layers were seen adjacent to the crack(s). This is an indication that the crack(s) were exposed to high temperature (austenitizing temperature) for some length of time; therefore, the crack(s) very likely existed prior to heat treatment. This condition is depicted in Figure 15.

Longitudinal and transverse samples were sectioned from material adjacent to the fracture surface. They were examined for inclusion content and microstructural evaluation. As-polished photomicrographs, Figures 16 and 17, revealed oxide-type and silicate-type nonmetallic inclusions, but this was strictly a localized condition. In general, the microstructure was clean and consisted of tempered martensite, as shown in Figure 18. Tempered martensite designates proper heat treatment.

CONCLUSION

Based on the findings of this investigation, we can conclude that the fracture during pressing was initiated at the quench cracks. However, the results of the magnetic particle, SEM, and metallographic examinations indicate that forging defects, i.e., bore surface cracks, were present in the subject gun tube material prior to heat treatment. Furthermore, these pre-existing defects, probably forging laps, acted as stress concentrators to initiate cracking during the quenching cycle of heat treatment. When the tube was then subjected to the stresses imposed by the straightening process, it fractured.

Examination of the forging process parameters did not reveal any discrepancies such as low forging temperatures or problems with the preform. Furthermore, inspection of the mandrel did not reveal any flaws or detrimental conditions that might have contributed to the defects (laps). It is possible that galling occurred between the workpiece and the mandrel, thus producing conditions during forging that caused the defects. However, this particular mandrel was in service for a substantial number of forgings after serial number 0242, so the initial conditions may well have been altered.

Although there was evidence of nonmetallic inclusions, they were not directly linked to a fracture initiation site, yet the forging defects were. Even though their cause was not determined, it should also be noted that since magnetic particle testing prior to the straightening operation had detected longitudinal cracks, further investigation (ultrasound) would have revealed the depth of the longitudinal cracks (3/8 inch deep) and located the circumferential cracks.

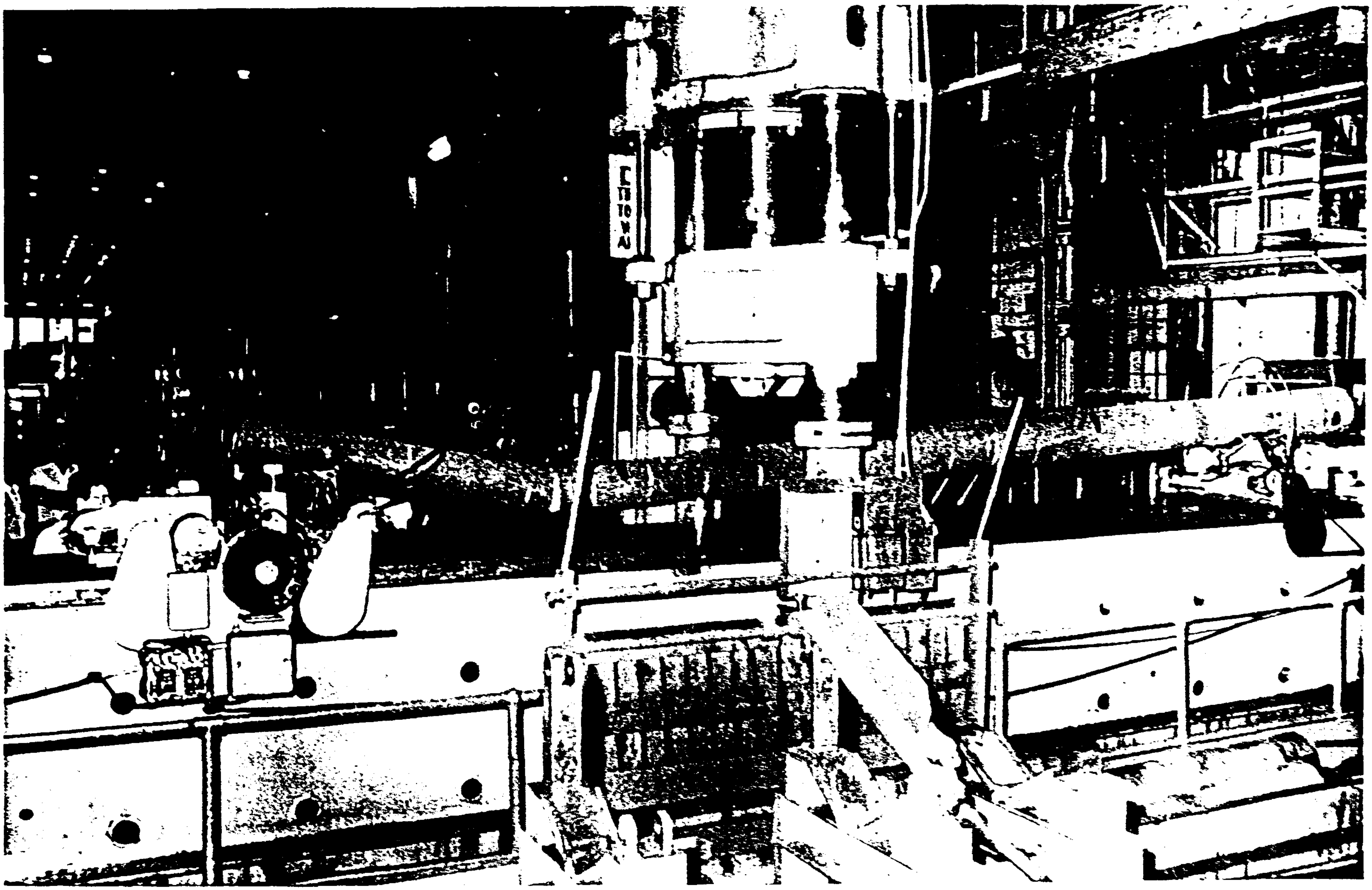


Figure 1. Fractured gun tube forging (serial no. 0242) on the straightening press.

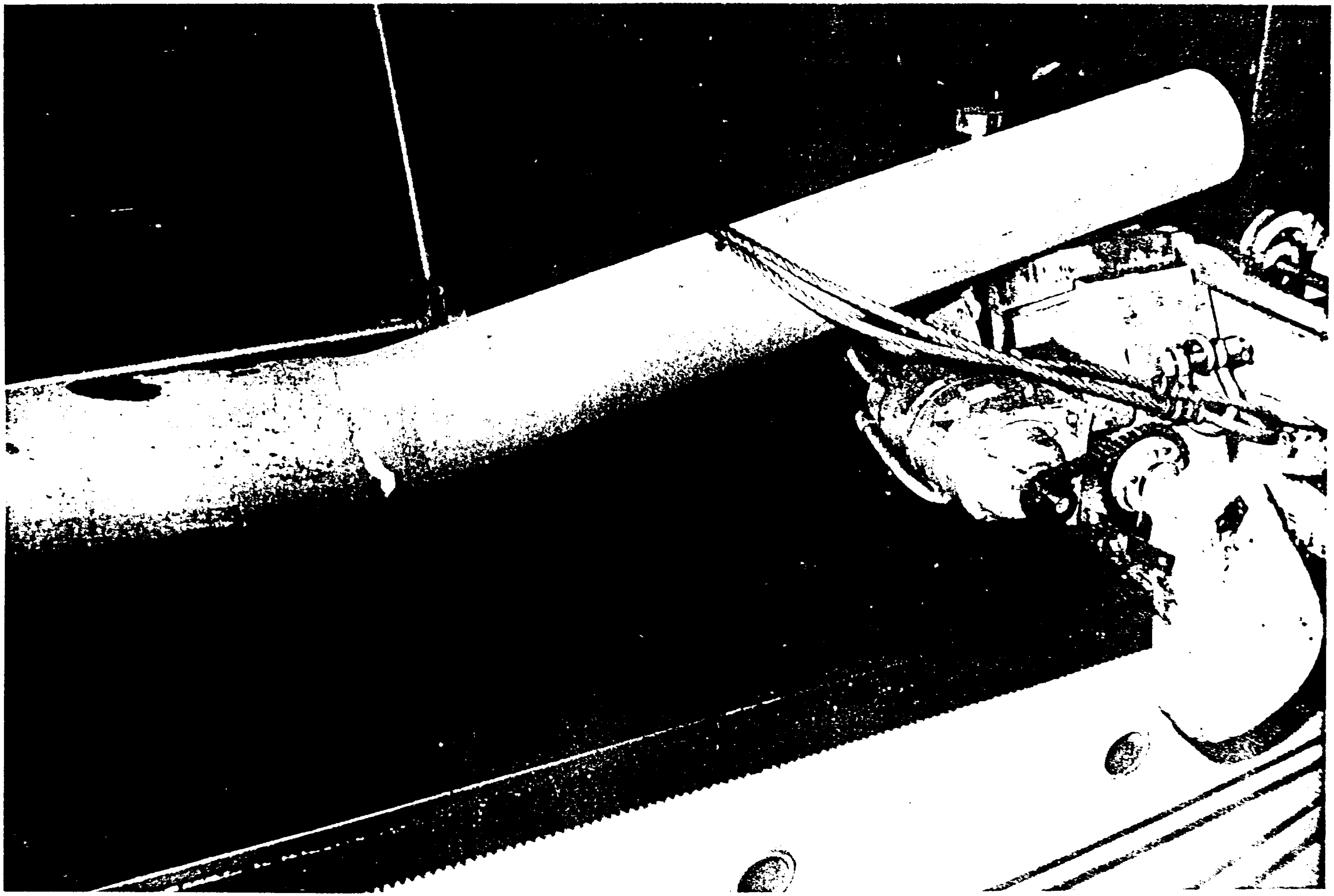


Figure 2. Close up of fracture on straightening press.

Figure 3. Segment of gun tube with fracture located near breech end (M1).

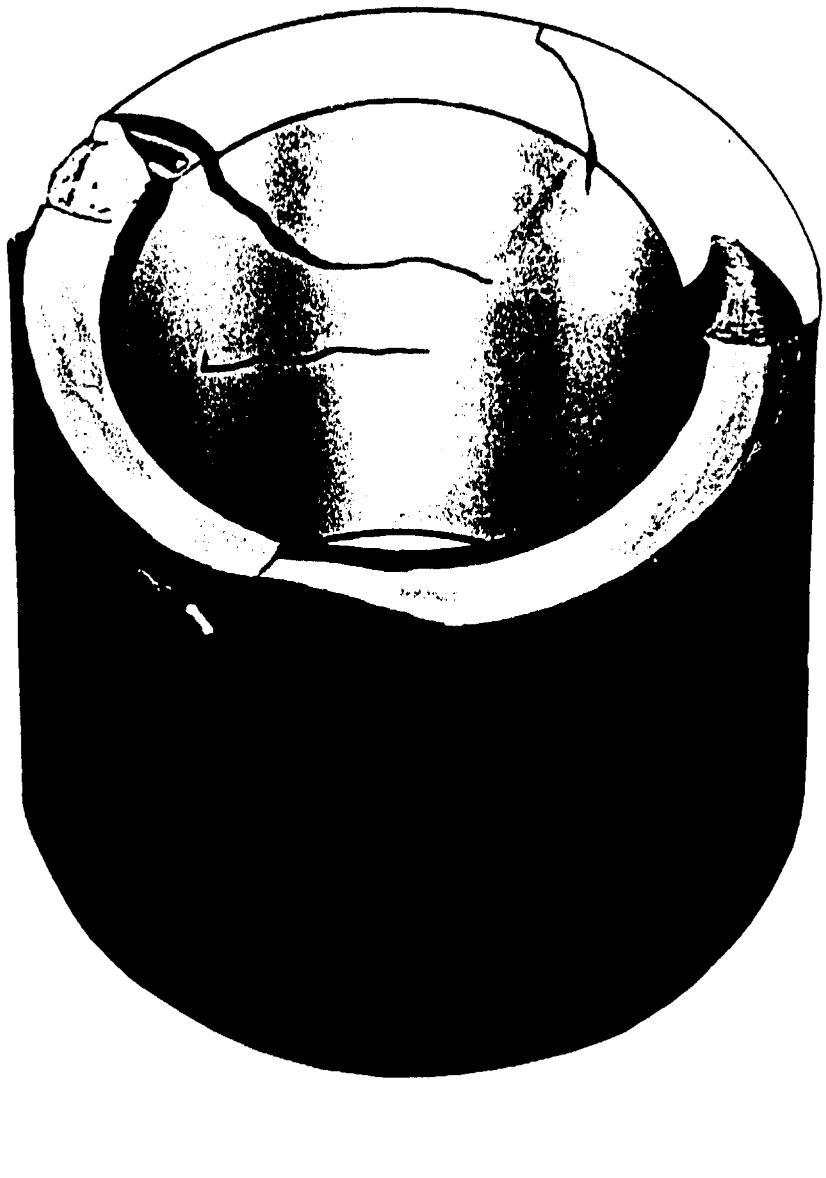


Figure 4. Segment of gun tube with fracture located near muzzle end (M2).

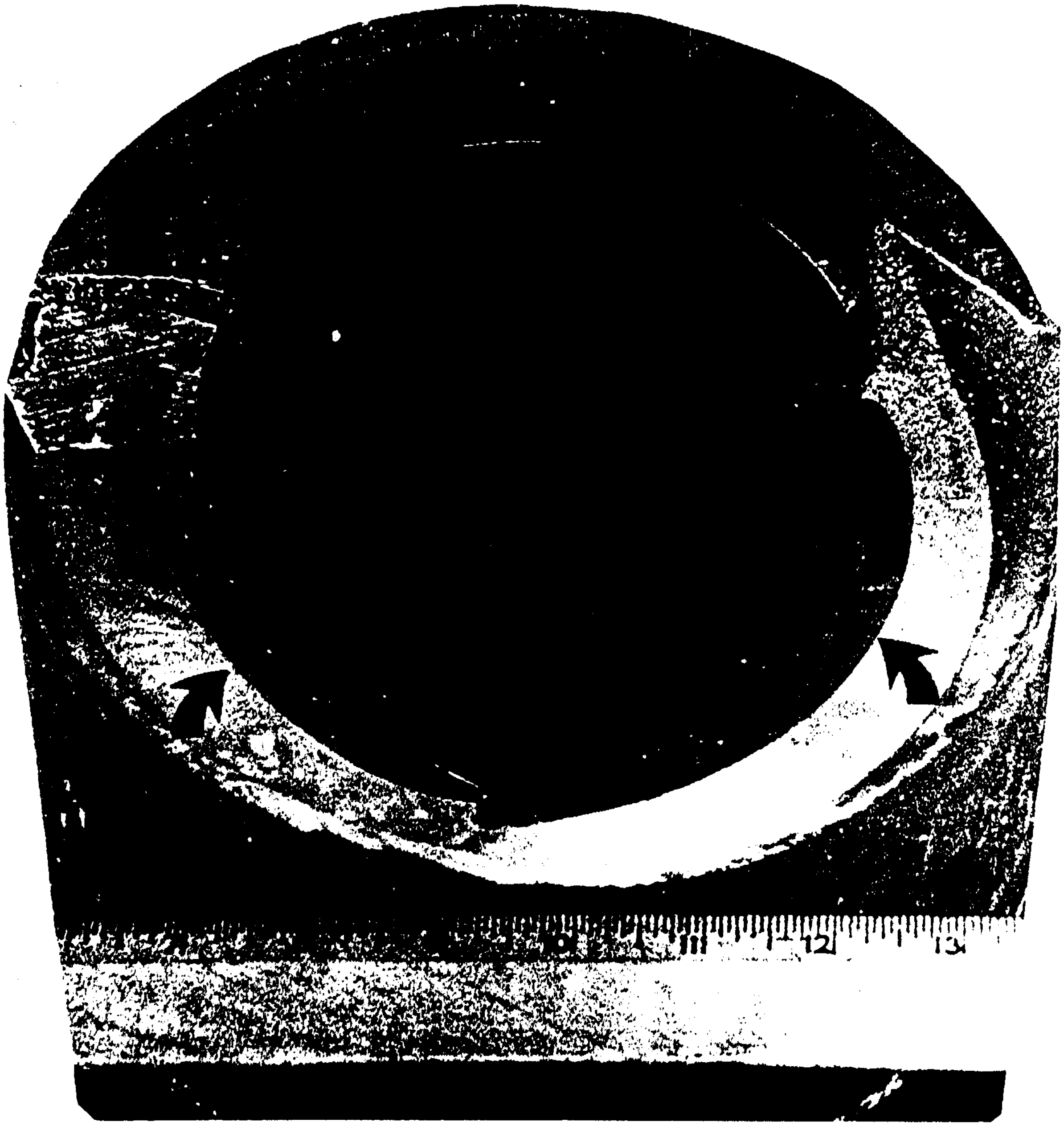


Figure 5. Dark gray ring on half of the fracture surface (end closer to the breech) (indicated by arrows).

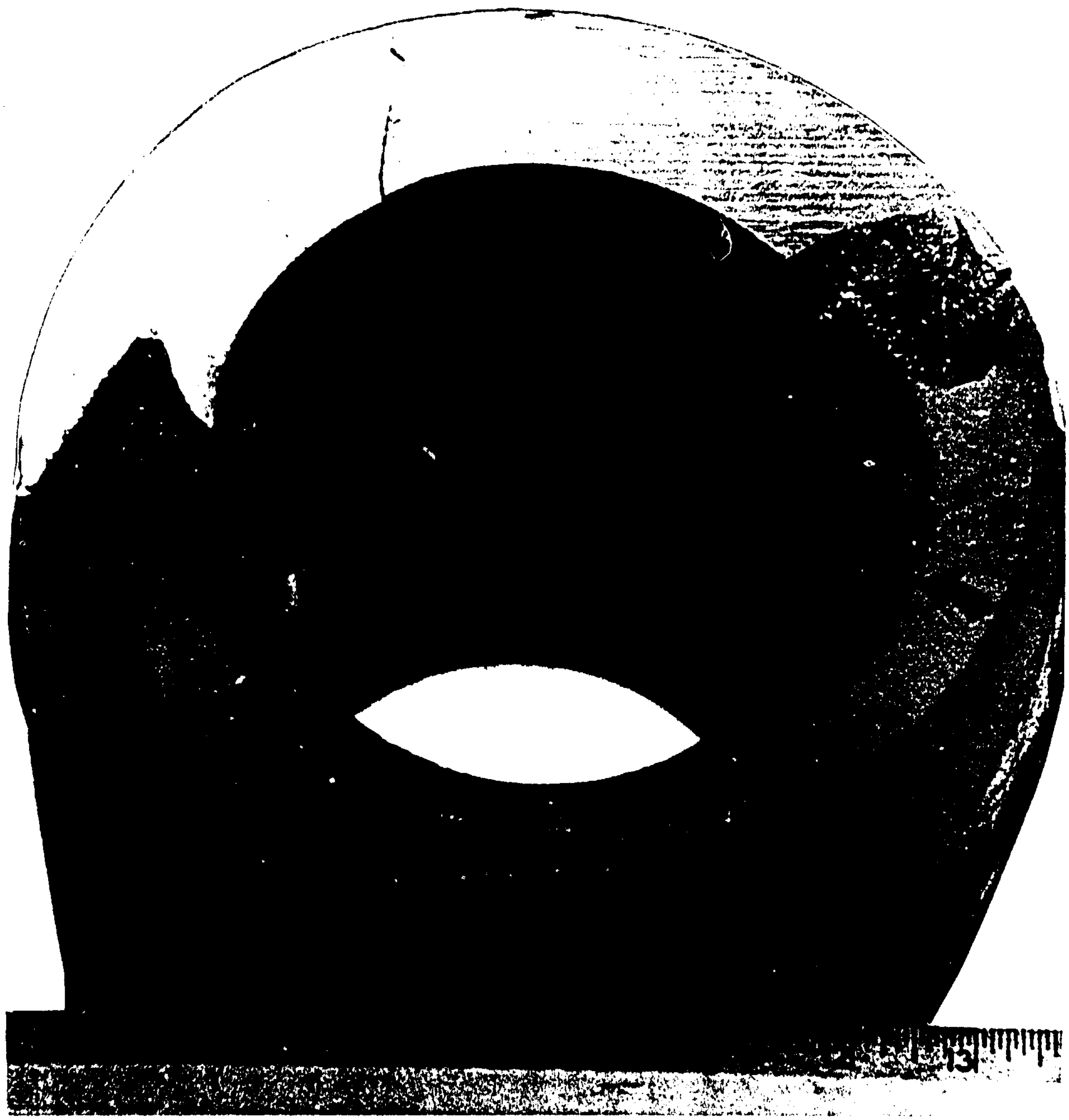


Figure 6. Dark gray ring on the mating half of the fracture surface (indicated by arrows).

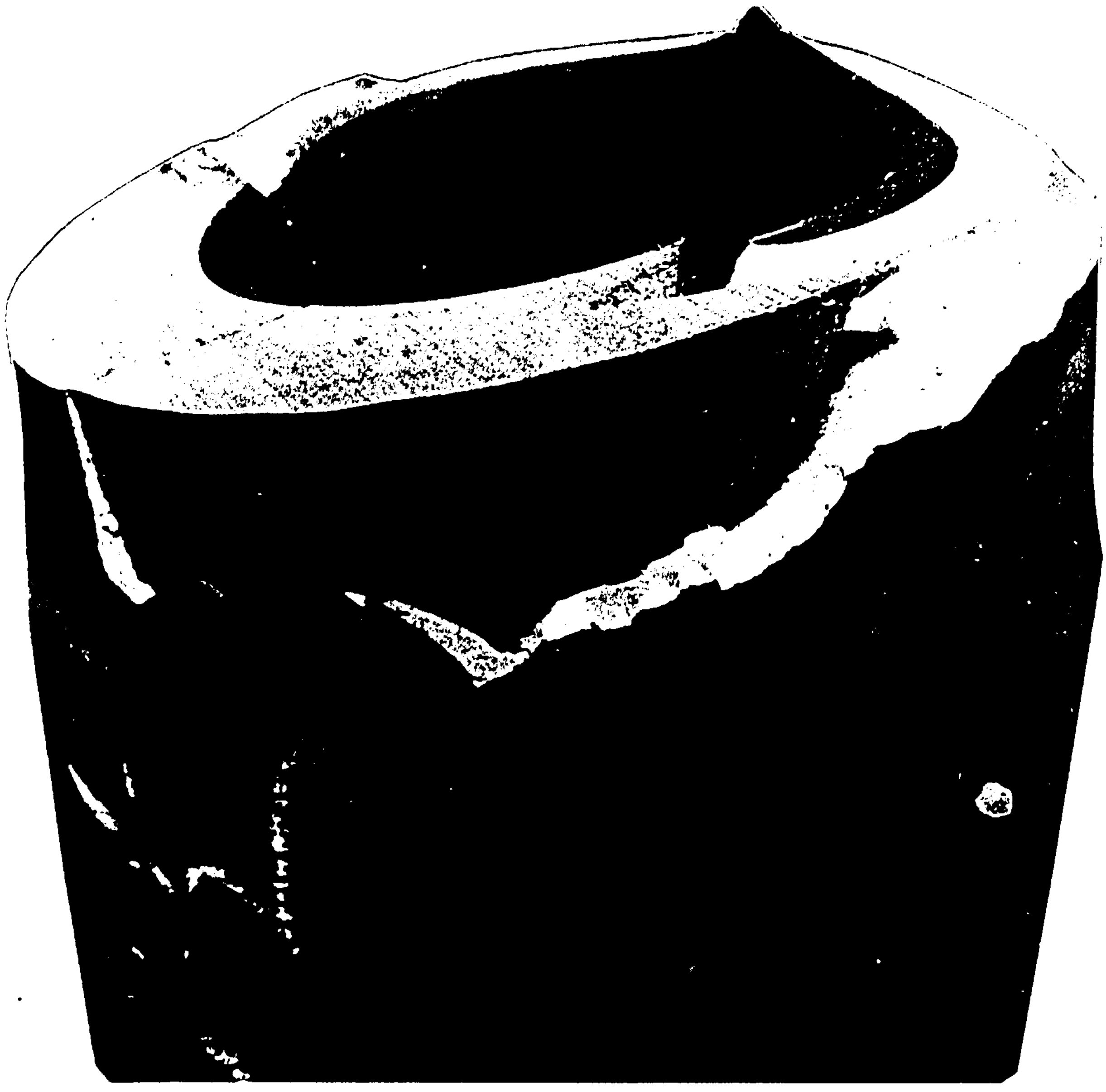


Figure 7. Side view of fracture surface showing secondary cracking (longitudinal direction).

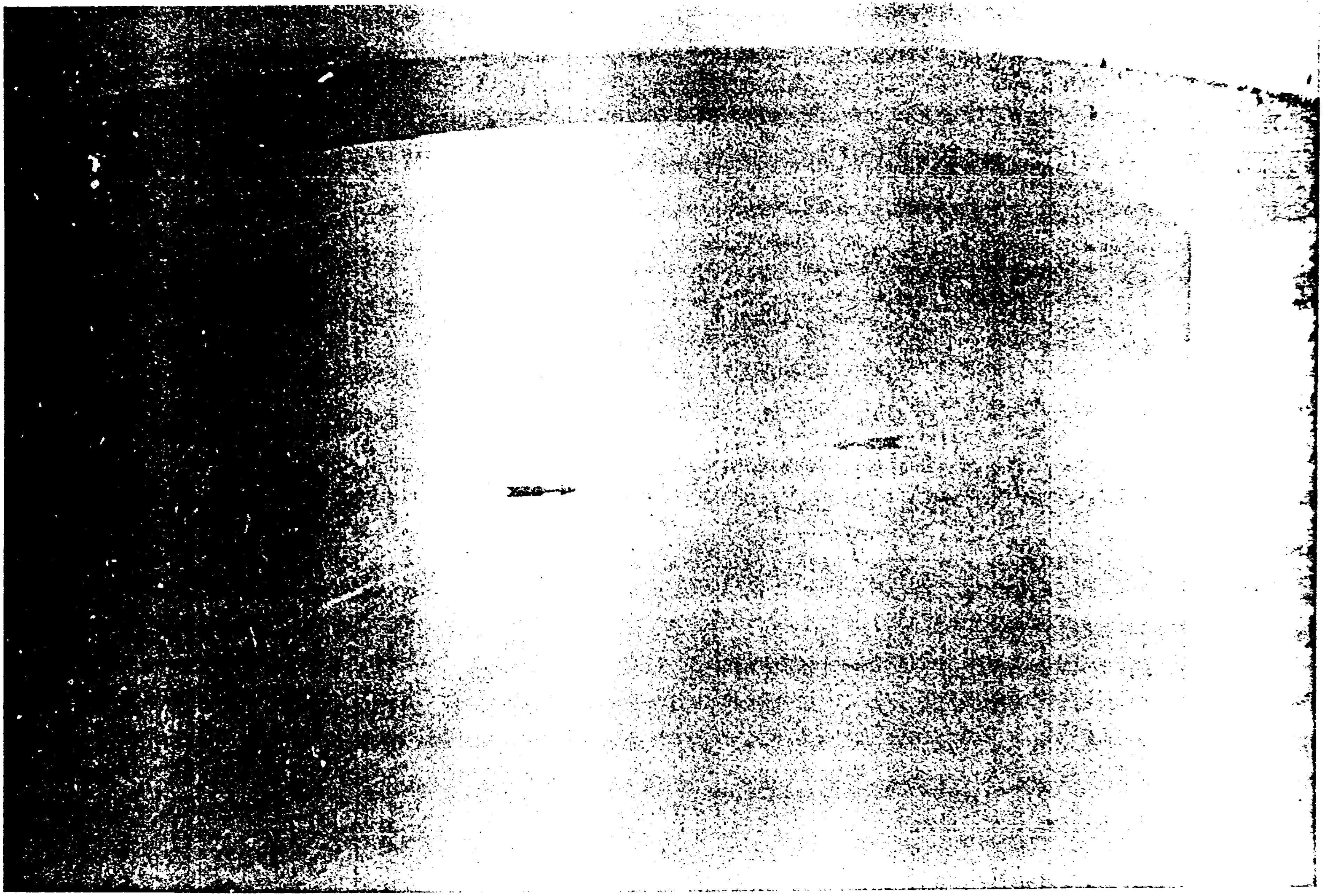


Figure 8. Magnetic [illegible] tion photo [illegible]
circum [illegible]

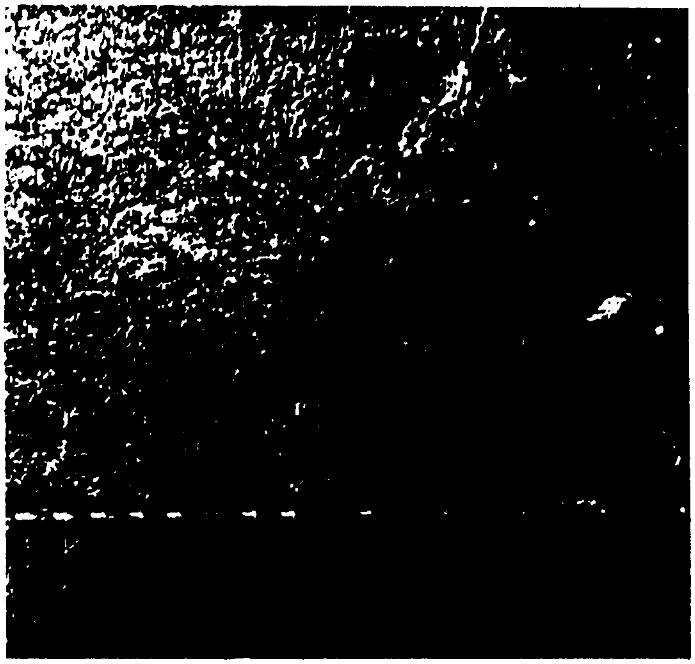


Figure 9. Small indications on bore surface (indicated by arrows).

Figure 10. Forging defect in the same direction of flow lines (20X).

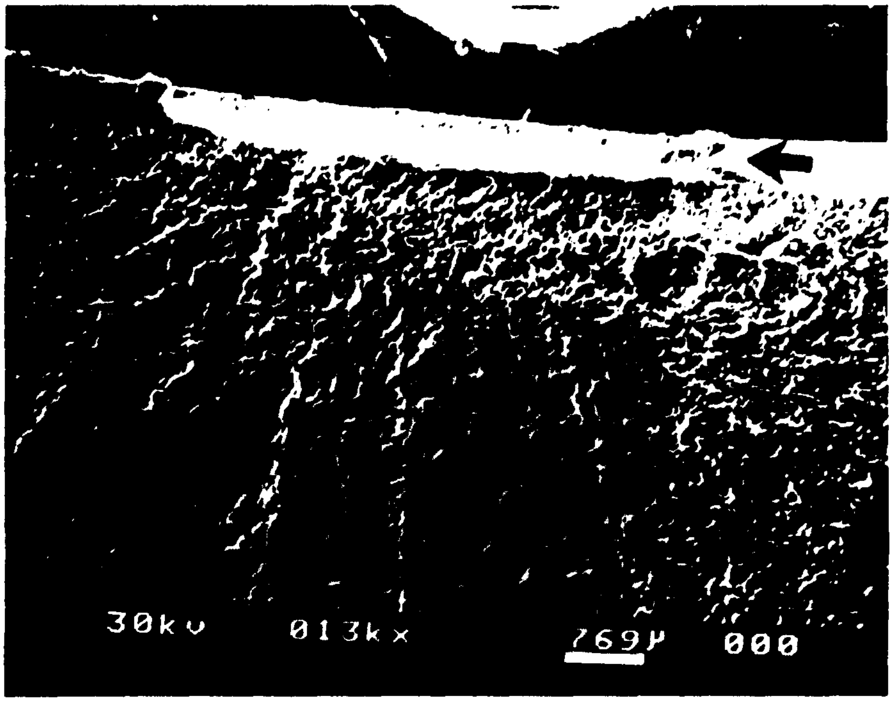
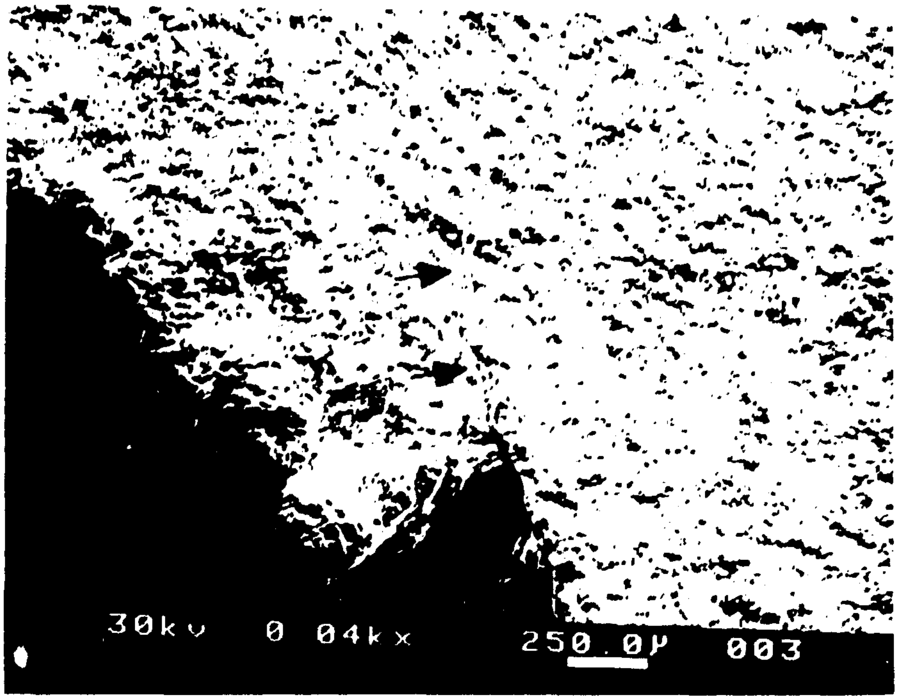
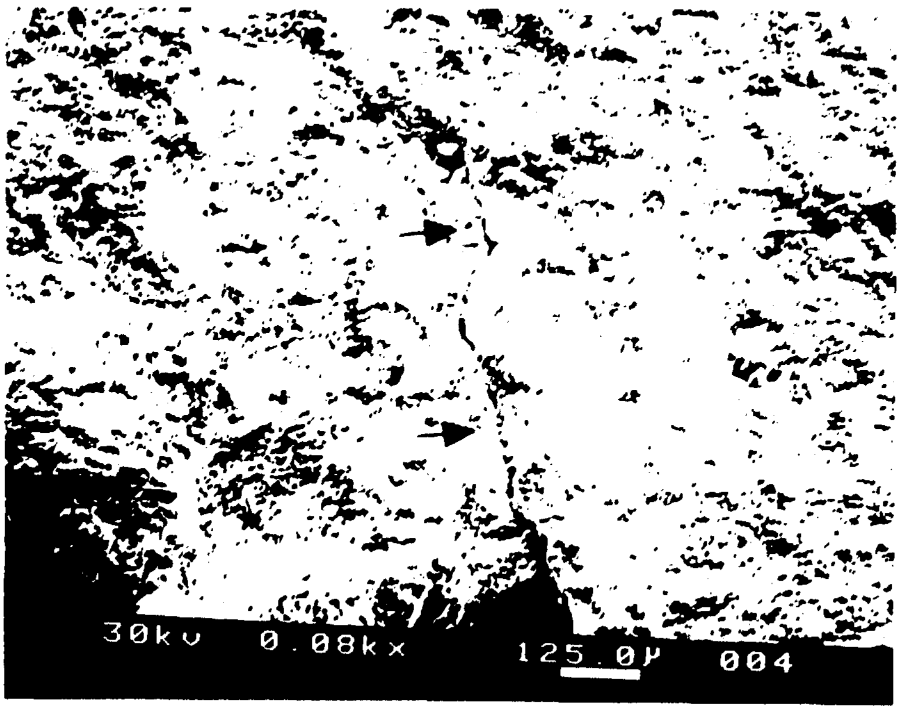


Figure 11. SEM of fracture origin
(indicated by arrows).



(a) 40X.



(b) 80X.

Figure 12. Fractographs showing crack depth.

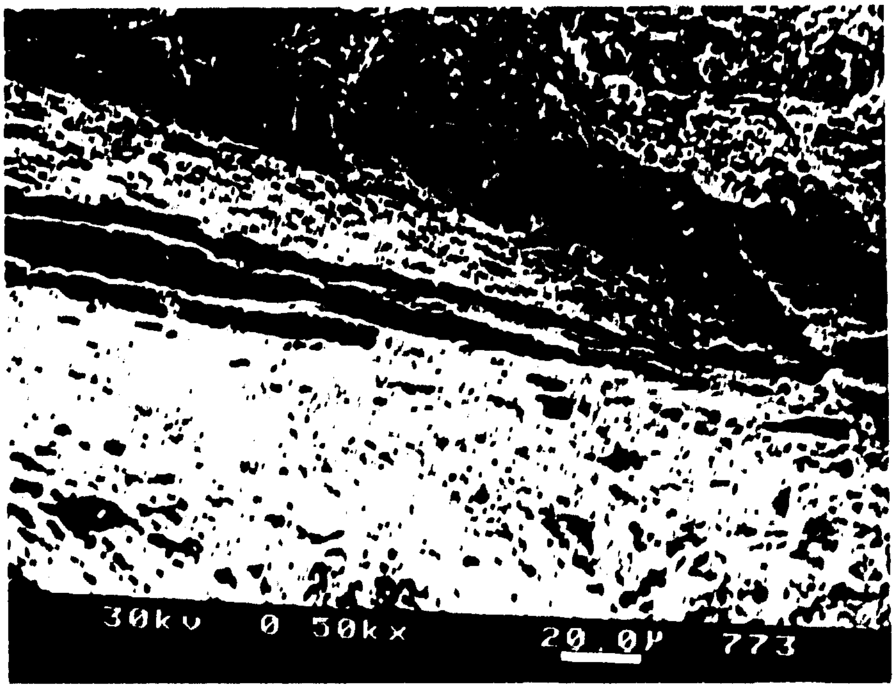


Figure 13. EDXA illustrating MnS inclusion (500X).

Figure 14. Forging defect depicting oxide layer inside of crack (100X).

Figure 15. Photomicrograph depicting decarbonization surrounding forging defect.

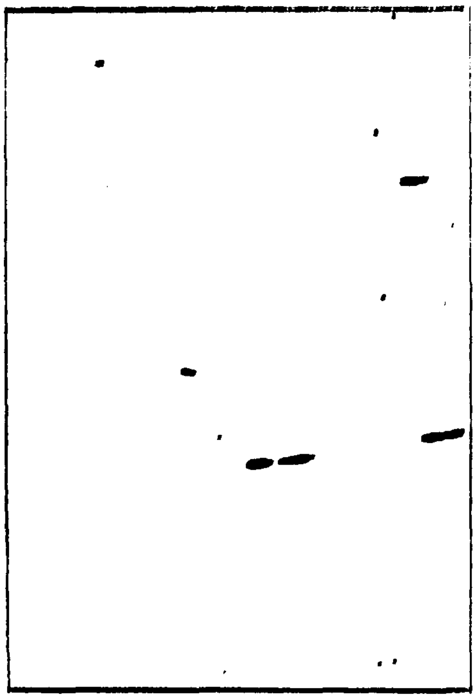


Figure 16. As-polished photomicrograph of longitudinal orientation (100X).

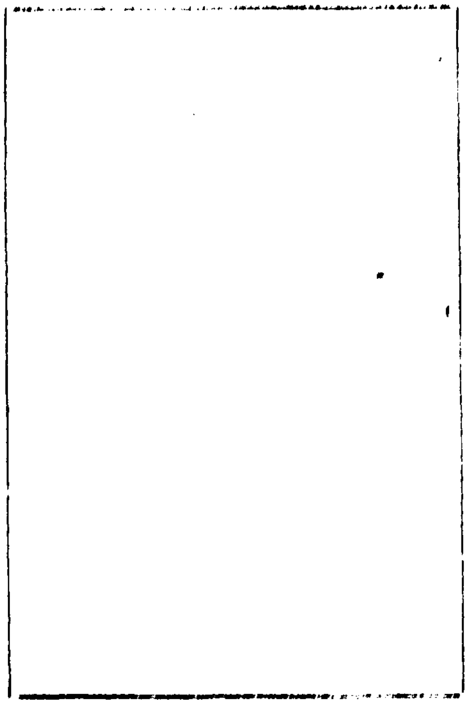


Figure 17. As-polished photomicrograph of transverse orientation (100X).

Figure 18. Tempered martensitic microstructure (1000X).

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